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PROCESSING AND ANALYSIS OF FIELD DATA OF TECHNICAL OBSERVATIONS--ETC(U)

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PROCESSING AND ANALYSIS OF FIELD DATA OF TECHNICAL OBSERVATIONS OF HYDRAULIC STRUCTURES AND THE EVALUATION OF THEIR SAFETY

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May 1978

CORPS OF ENGINEERS, U.S. ARMY
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The primary purpose of field investigations in the USSR, as in other countries, is monitoring the condition of important hydrotechnical structures during their construction and during their operation. The scientific-methodological questions associated with field investigations, although important are resolved by means of using the material derived from observations which are purely applied in nature.

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PROCESSING AND ANALYSIS OF FIELD DATA OF TECHNICAL OBSERVATIONS OF HYDRAULIC STRUCTURES AND THE EVALUATION OF THEIR SAFETY

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In the USSR, a project of field investigations of hydrotechnical structures of the third class or higher is compiled simultaneously with the project of structures of the hydrotechnical facility. The USSR has no nationwide standard which governs the volume of field investigations on these or other bearing structures (structures under pressure). However, the leading (main) Scientific Research Institute in the field of hydraulics has published documents of industry-wide significance (L. 1, 2, 3)*, which are recommended for use within the confines of the Ministry of Energy and Electrification. These documents encompass the primary organizational scientific-technical and methodological questions.

The primary purpose of field investigations in the USSR, as in other countries, is monitoring the condition of important hydrotechnical structures during their construction and during their operation. The scientific-methodological questions associated with field investigations, although important, are resolved by means of using the material derived from observations which are purely applied in nature.

2. Processing the Material of Field Observations.

2.1. Processing the Data of Field Observations at the Construction Site Should be Proceeded by a Combination of Extremely Important Operations:

a) the installation of instruments in the structure in accordance with the project and ensuring their preservation and functioning capacity;

b) compiling the executive documentation (blueprints, acts of the supporting administrations, etc.);

c) compiling the schedule of taking readings from the installed instruments;

d) setting up time commutators to take readings from instruments during the time of construction;

e) making a list of factors which should be supplemented by instrument

*) Only the most significant documents have been cited.

reading data (summary meteorological data; the beginning and end of the tubed coolant, the temperature of cooling water; times of pouring foundation cement, screen cement, and cement in the interblock seams; data on pouring adjacent and higher blocks, etc., necessary information).

The accomplishment of the work listed above fully and at a sufficiently high technical level facilitates the comprehensive analysis of observational results to a significant extent as well as the most complete and objective derivation of a conclusion regarding the condition of the structure.

2.2. Primary Processing of Observational Results.

Primary processing of observational results, as a rule, pertains to determining the measured values (deformations, temperatures, pressures, forces, etc.) according to the data of direct measurements of frequencies, resistances, induction factors, etc. Primary processing is carried out at the construction site itself and is intended for maintaining operational control over the condition of separate components of the structure (temperature in the concrete blocks, threshold pressure in the earthen dam screens, forces active in the reinforcing rods, etc.). The most efficient technology of building the structures is developed on the basis of these data.

Primary processing also facilitates operational control over the reliability of obtained readings and the working order of the laid (concrete-inserted) and measuring apparatus.

2.3. Secondary or Analytical Processing of Observational Results.

Unlike primary processing, secondary processing produces a broad overview for the investigator and can take varied forms.

The use of computer equipment here is not only desirable, but is unavoidable, as a rule.

Certainly, the basic purpose of secondary processing of field observational results is an overall evaluation of the condition of the hydraulic center structures and compiling recommendations on optimum regimes of operating structures, maintenance-preventive measures, and the future system of observing the structures.

Simultaneously, the results of field observations produce extremely valuable material about the factual condition and function of structures. This material is processed appropriately and can be successfully used to correct methods of calculation, modelling investigations, and for designing new hydraulic structures at a higher technical level.

The attempt to unify methods of secondary processing of field research material has led in the Soviet Union, to a certain extent, to the development of an appropriate manual (L. 4).

It should be noted that it is conventional to process the readings of

implanted instruments in the USSR, practically speaking, beginning with the time of their installation in the structure. On the one hand, such a method makes it possible to follow the phenomena which occur in structures during their construction, and on the other hand makes it possible to identify the functional capacity of the installed instruments in advance of the time of their required use.

2.3.1. Processing Field Observations of Concrete Dam Movements.

At present, it is generally recognized in the USSR and abroad that general movements are one of the most important characteristics which determine the condition and function of a structure in the most complete, integral form. In the final analysis, all slow and sudden changes which occur within the structure of a dam's body or a dam's foundation are associated to one degree or another with structural motions. A particular place in such motions is taken by horizontal displacements which most "clearly" react to all changes and can be easily measured at any moment in time with the aid of direct and inverse plumbs with a high degree of precision. Therefore, the most intent attention is paid to observations of horizontal displacements in both the USSR and in all foreign countries as well as to processing the results of measurements.

One can estimate measured displacements chiefly with the aid of known theoretical relationships of structural mechanics, according to which one calculates the elastic and thermal displacement components. In this case, the irreversible component is defined as the difference between the measured displacement and the total of the elastic and thermal components. The physico-mechanical characteristics of the dam and foundation which are necessary for calculating the elastic and thermal displacements are determined according to theoretical formulas in which Young's modulus of the concrete or rock and the linear expansion factor are functionally associated with one or more measured values (horizontal displacements, settlement, turns and warps). The calculated values obtained according to the approximate relationships cannot provide a preicse prediction of the behavior of the structure and its foundation, inasmuch as they do not pertain to the actual condition of the structure but rather to a certain mechanical model which forms the basis of the projection.

As a rule, methods of so-called comparative analysis of measured displacements are more frequently used. Comparative analysis predicates the exclusion of one or two factors which determine the displacement of the structure. The method of successive approximations from the total measured displacements excludes elastic and thermal components and determines the irreversible displacements. The character of their changes in time makes it possible to evaluate the function of the structure under load and to identify anomalous phenomena which could arise. Displacements of the Mamakansk hydroelectric power plant dam were analyzed by this method (L. 5).

With the introduction of the computer into engineering practice, a statistical method became widely used both abroad and in the USSR. This method makes it possible to identify the reaction of the dam to each separate factor. The method not only makes it possible to estimate the function of the structure at

a certain moment, but also to predict the function in the future (L. 6). This method was used to analyze measured displacements of the Krasnoyarsk, Bratsk and Bukhtarmin dams. In order to analyze measured displacements of the crest of the dam, the following algebraic expression of the mathematical model was accepted on the basis of available foreign and Soviet experience:

$$U = \delta_1 H + \delta_2 H^2 + \delta_3 H^3 + \delta_4 \cos\frac{2\pi}{365}\tau + \delta_5 \sin\frac{2\pi}{365}\tau + \delta_6 \cos\frac{4\pi}{365}\tau + \delta_7 \sin\frac{4\pi}{365}\tau + \delta_8\left(1 - e^{-k\tau}\right) + \delta_9 + \varepsilon \tag{1}$$

where the first three members express displacement due to the action of reservoir water on the dam, the following four members express the thermal displacement, the eighth member expresses irreversible displacement, and the ninth - free member - represents thermal displacement when measurements began; the tenth member represents measurement errors; U is measured displacement at a moment τ; H is the change in the water level in the reservoir at a moment in time τ; δ_1, δ_2, δ_3 are coefficients of the effect of water level in the reservoir; δ_4 - δ_7 are coefficients of the effect of ambient air temperature; δ_8 is the time effect factor τ. Relationships of the type (1) were devised for each moment of measurements carried out during the first two years of operation, and the effect factors of δ_i were determined by the method of least squares by means of solving the obtained system.

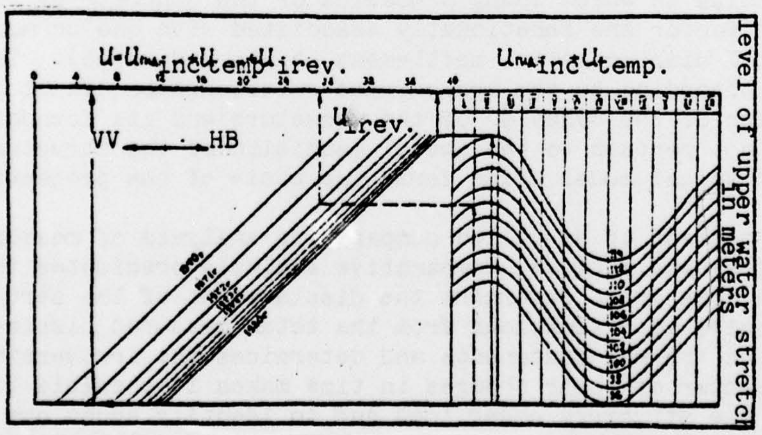

Figure 1. The Krasnoyarsk dam. Nomogram of controlled crest displacements.

These were used to estimate the effect of the actual factors on displacement: hydrostatic pressure, ambient air temperature, and time; i.e., the elastic, thermal, and irreversible displacement components were determined. A nomogram was plotted according to these data, associating the displacements, water level

in the reservoir, ambient temperature and the time factor (Figure 1). With the aid of the nomogram, in which the monitored (predicted) values of displacements are represented in a function of the factors active on the structure, dam operating personnel have the possibility of estimating the result of any observation (measurement). Control over functioning of the structure is maintained by means of comparing the displacement measured at any moment of operation with the appropriate control value. A sharp deviation between the measured and predicted displacements is a signal of the appearance of an anomaly in the function of the structure.

Measured displacements of the crest of the Bukhtarmin dam were similarly analyzed. Analysis of displacements of the Bratsk dam was distinguished by the fact that the parameter which determined thermal displacement of the structure was not ambient temperature in relationship (1), but temperature of the concrete in the lower face of those sections where the screens were located.

Freezing of the concrete and expansion of the construction joints on the lower face lead to an alteration of the thermal component. The conducted analysis demonstrated that the thermal component of displacements is twice smaller for the Bratsk dam in Winter than in Summer.

2.3.2. Processing Field Observation Data of the Filtration Regime

Recently, the employed determined approach to setting up field filtration observations used until now has been subjected to quite justified criticism from the standpoint of formal logic. With such an approach, the natural unordered heterogeneity of the filtering media and the selective character of results of local and discrete measurements of the monitored parameters have been totally ignored and the possibility of developing a theoretical base for the method of a directed search for local heterogeneities of the filtering medium has been excluded. Correspondingly, the possibility of determining the system of observations necessary and sufficient for conducting the referenced search has been principally excluded. In order to have a motivated solution to the problem of the sufficiency of any particular monitoring system, it is primarily necessary to refrain from the employed heterogeneity of the studied object a priori. Consideration of unordered heterogeneity of actual media and of the changeability of the value of the monitored parameters in time leads to the fact that in an overwhelming majority of cases the values of the observed parameters which represent the results of discrete measurements are local in nature and should be viewed as a certain selection from the general totality of values of the monitored parameter. In this case, an estimate of the values of the controlled parameters according to the results of field observations is a task of finding true values of a certain random magnitude or a random function and the general characteristics which define it according to selective data. The probabilistic character of this estimate makes it possible to substitute the known methods of statistical analysis in order to determine the sufficiency of the assigned set.

The statistical approach to solving the problem can require an increase in the information which is sufficient to obtain results with a defined degree of accuracy. The solution to the problem of the sufficiency of information lies in finding the maximum and the minimum in comparing the value of the obtained

information and the expenditures necessary for this purpose.

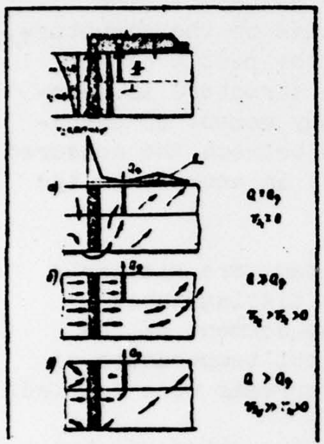

Figure 2. An auxiliary diagram for analyzing regular observational data.

I - stress-strain diagram of the piezometric pressure head; II - filtration pressure stress-strain diagram; III - screen; IV - drainage.

$v_{3_{1,2,3}}$ - rate of filtration flow through screen in cases, a, b, respectively; Q - filtration flow rate in foundation; Q_g - drainage flow rate.

The general deficiency of information obtained from the generally employed systems of filtration control becomes particularly noticeable when one identifies a direct necessity of testing the suitability of calculation systems which are used in making the filtration calculation. For purposes of illustration of the above, Figure 2 shows an example of monitoring a concrete screen whose functioning conditions can correspond to different calculation systems depending on filtration characteristics of the filtering media. It is evident from this figure that the interpretation of field data depends significantly on the calculation system employed. The information increase required in such cases can be ensured by a corresponding expansion in the composition of observations, predominantly aimed at studying the velocity field of the filtration flow.

2.3.3. Processing the Data of Field Observations of the Stressed-Deformed State of Concrete Dams

As was noted above, processing data obtained according to inserted instruments, primarily extensometers, begins immediately after the time of installing the instruments in the block.

Observations of the stressed-deformed state of concrete dams during their construction have made it possible actually to establish that so-called technological stresses arise in such dams, without whose consideration analysis of the stresses which act in the structure during its construction is essentially impossible (L. 7). These same observations have made it possible to establish that the physico-mechanical properties of frozen concrete differ sharply from those of melted concrete. Under severe climatic conditions, this factor leads to a significant change in the stressed state of concrete dams in Winter, when the lower face of the dam freezes to a depth of 6 - 7 m (L. 8, 9).

The observational results are naturally processed using the basic tenets of the theory of elasticity and the theory of the elastic-creeping body. An overwhelming volume of calculations are computerized. For this purpose, extremely detailed programs have been compiled which not only make it possible to obtain the value of stresses for any areas, but also to identify errors that have been made when taking instrument readings.

The calculation of creep is made according to relaxation curves which are obtained on the basis of the appropriate testing of 5 - 7 sample series with four samples per series. It is permissible to employ standardized relaxation curves obtained on the basis of generalizing the results of testing samples at a number of objects (the Bratsk, Krasnoyarsk, and Bukhtarmin hydroelectric power plants) (L. 10).

In certain of the most complicated cases, for example, when calculating the change in physico-mechanical characteristics of frozen concrete, the method of finite components is employed when processing field observation data. This method is presently most widely used with a limitation imposed by the significant laboriousness of the preparatory work.

Field observational data of deformations and their analysis and processing have significantly expanded our concepts about the function of hydraulic structures under the effect of external load and temperature.

It should be noted that the investigation of the stressed state in the Soviet Union does not presently employ concrete dynamometers, which are intended for the direct determination of stresses in concrete. Experience in installing these instruments has not produced reliable positive results. The preparation and installation of these instruments are associated with a number of difficulties which are not always successfully eliminated and the theoretical foundation of these measurements, in the opinion of a number of specialists, is insufficiently established.

2.3.4. Processing the Data of Field Observations of the Thermal Regime of Concrete Structures.

The data of observations of the temperature regime are processed in a particularly large volume during construction. These data are used to develop a technology of concrete pouring operations and the artificial cooling of concrete. As a rule, for these purposes, the simplest processing of instrument readings is sufficient. Such processing pertains to determining temperature in a point, and, seldom, to plotting stress-strain diagrams of temperature through the block (structural) cross-section.

However, in certain cases, isotherms are plotted for the examined structural cross-section according to the data of field observations of temperature at separate points. Plotting isotherms is expedient for the purpose of making an additional analysis of the stressed state of a structure and for predicting its possible future change. It is also expedient for estimating the effectiveness of employed methods of cooling the concrete pour batch and for prescribing additional measures to improve these methods.

Without dwelling further on methods of processing the data of field observations, we shall only note that such observations can be of the most varied character and that investigators have a broad horizon for creativity in respect to this question. It does not seem possible to standardize the potential methods of processing, nor does it seem expedient to do so. Here one could only provide certain recommendations which were mentioned above (L. 4).

3. Estimating the Safety of Hydraulic Structures.

As a rule, qualified personnel can estimate the condition of a structure with an adequate degree of reliability according to the data of field observations conducted according to a clearly formulated diagram and in the required volume.

However, such an a posteriori method cannot serve as the basis for evaluating the safety of a hydraulic structure inasmuch as such an estimate of a load bearing hydraulic structure must be given in the operational order, systematically, and, if need be, daily or hourly, precisely the same as information about the function of a steam boiler under load, for example. The experience gained from serious catastrophies which have occurred at hydraulic structures is a merciless indication of this situation.

Two interrelated large problems arise during solution of the posed problem.

The first is automating and centralizing the measurements of instrument readings and processing such measurements.

The second problem is developing criteria of the safe operation of the structure which would make it possible uniformly to evaluate the condition of structures from the standpoint of their safe operation.

Questions associated with the first problem exceed the framework of this report and are not subsequently examined. It is only important to note that controlling the safe condition of structures requires that this problem be unconditionally solved.

The criteria of control which are necessary in order to evaluate the reliability of a structure and to predict its condition over long periods of time should be based on clear-cut, all-encompassing concepts about the conditions of operating the structure and its separate components and on characteristics of the component's maximum permissible state. In the modern literature, up to now, the data needed for extensive general conclusions have been absent. Therefore, at this stage of development of the methodology of inspecting structures presently being built and now in operation, one can only discuss ways of solving the posed problem.

3.1. Criteria of the Safe Operation of the Structure.

The criterion of the safe operation of a hydraulic structure means the physical value which most fully, in an integral form inasmuch as possible, characterizes the condition (operation) of the structure and which can be efficiently measured with existing technical devices.

When designating the criteria of the safe functioning of structures, the question primarily arises of what one can and expediently take for the criteria.

The modern level of our ideas, technical possibilities, and practical experience enable one to approach the solution to this problem in the following way.

It is expedient to take the following as criteria for concrete dams: general (chiefly horizontal) displacements; the filtration regime (pressure, flow rate, velocity gradients); the stressed state (for high and lightened structures); the thermal regime (chiefly in the construction period).

For earthen dams: general (chiefly vertical) displacements; the filtration regime; pour pressure (chiefly in the construction).

Certainly, the enumerated list permits designating such criteria as seam opening, the formation of ice and hoarfrost, vibration, etc. as such criteria, in certain cases.

It is necessary to continue the search for other criteria which more fully and reliably characterize the state of structures. At the new level of our knowledge, possibly, such a criterion could be the spectrum of natural oscillations of structures, for example; their decrement of damping, or other criteria.

3.2. Determining the Criteria of Safe Operation of Hydraulic Structures.

By the time of the first filling of the reservoir, criteria of its safe (normal) operation should be defined for each hydraulic structure (particularly the structures under high pressure). Observations over these under field conditions must be the basis for evaluating the state of the structure.

Naturally, criteria can be given at this stage which are of a purely calculation type, and certainly involve the use of data of measurements, laboratory, and modelling investigations.

With the appearance of factual data of field observations and processing of such data, one gets the genuine possibility of refining the issued criteria and of making corrections into the criteria issued in advance but which are of a purely a priori character.

Proportional to the accumulation of the factual material and obtaining a reliable correlation relationship between the measured values and the loads (factors) in effect at the structure, it becomes possible to transfer the center of emphasis away from the a priori (purely theoretical) methods in the determination of criteria to the a posteriori methods and statistical methods which utilize the factual observational data.

In this case, certainly, the degree of reliability and the justification of the accepted values of reliability criteria of the structures increase.

Together with this, two significant questions additionally arise. These questions require resolution when imposing operational control over structural reliability.

First, it is necessary to establish the nature of the possible change in monitored values in time, and, in this regard, to designate action times of the issued recommendations in advance of their use.

Second, it is necessary to estimate the limits within which deviation of the actually measured values from their values issued as the safety standard and standard of reliable functioning of the structure is permissible.

Both of these problems are separately solved for each specific object depending upon the object's design features, the conditions of accomplishing the work, natural conditions, the reliability and completeness of information obtained during field observations of the structures, etc.

Figure 1 shows a nomogram which can be given as an example of a structural reliability criterion for displacement. The scatter of points obtained during the solution of equation (1) made it possible to recommend using the supplementary factor analysis when the actually measured values deviate from the nomogram by 15% or more.

Strictly speaking, the examined graph actually cannot be the criterion of safe functioning of the structure (dam) until the measurements made according to the plumbs are automated and the results of the measurements are automatically plotted on the nomogram graph.

One can suggest using the so-called current control criteria as the first step in determining the reliability criteria based on the results of observing the filtration regime. The criteria of current control are designed for freeing the researcher from having to analyze random fundamental changes in the observed values. Such changes occur during filtration in media with practically constant filtration characteristics for when the changes of such characteristics do not threaten to disrupt the normal operating conditions of the structure. Criteria have been issued for this purpose in which the method of determination is a known generalization. Thus, for example, the development of the method of determining current control criteria which correspond to filtration conditions uinformly determined by water levels has been developed. In order to evaluate the permissible heterogeneities of the medium, one introduces criteria of heterogeneity established according to data of field observations using the results of theoretical and laboratory developments. The so-called search criteria used in solving industrial problems associated with finding local weaknesses comprise one variety of these criteria. The criteria of current control, whose development is associated with the determination of anomalous deviation factors from the predicted values of measured parameters, are included in a special group. Finally, a method of determining criteria of the permissible intensity of controlling suffosion processes at the object has been developed.

The determination of current control criteria can be illustrated based on the example of organizing observations over the piezometric pressure head in the left bank earthen dam at the Bratsk hydroelectric power plant. The rocks which directly underlie the foundation of this structure are anisotropic, cracked, and are distinguished by a high permeability to water in the horizontal direction. The flow in the lower stretch of water is unloaded with the aid of systems of powerful drain devices and the hydraulic relationship of the filtration flow with the lower stretch of water is practically absent.

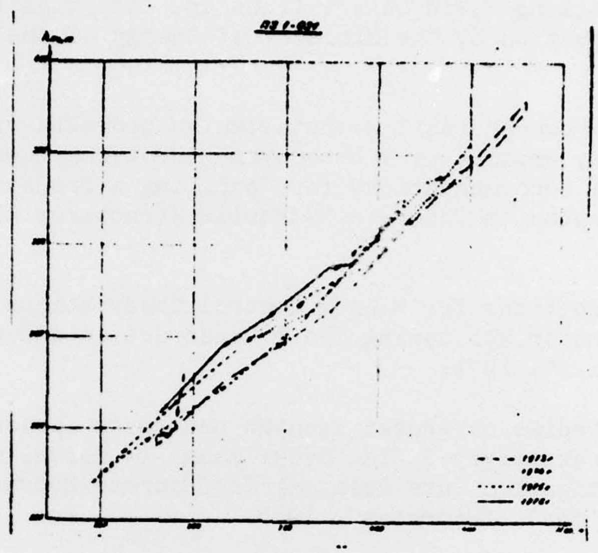

Figure 3. The relationship of water levels in piezometers with the level of the upper stretch of water.

In the case of the created situation, when the pressure of the filtration flow in the unaltered filtration medium of the rocks is solely determined by the level of the upper stretch of water, the corresponding graphs of the relationship of the piezometric pressure head at the individual observation points and the level of the upper stretch of water should be represented by standard curves with an assigned maximum value of the permissible point scatter. When these points are connected in chronological order under conditions of periodic fluctuation in the level of the upper stretch of water, the indicated graphs are usually represented by several families of superimposed broken lines. The presence of a certain tendency toward displacement in the layout of such lines indicates a change in filtration conditions. The typical graphs of the relationship of the piezometric pressure head in the individual observational points with the level of the upper stretch of water are shown in Figure 3, with the condition of a constant and changing filtration resistance in the control sector. Figure 3 clearly shows a progressive increase in the pressure of piezometer No. 1-031, which indicates, as an additional analysis demonstrated, suffosion phenomena in the area of the foundation which is monitored by this piezometer. The indicated relationship graphs were accepted as one of the fundamental justifications for carrying out repair work on the given stretch.

The cited examples indicate that questions of determining reliability criteria in the Soviet Union are being given definite attention. However, precisely the same examples also demonstrate that the examined question still leaves many unsolved problems. A great deal of complicated work still remains to be done.

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